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FURTHER STUDIES OF MAGNUS PHENOMENA
ON SPINNING AND CONING BODIES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
AEROPHYSICS LABORATORY

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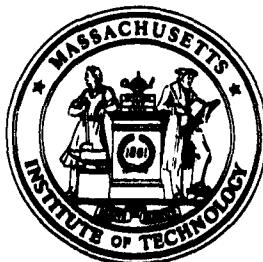Cambridge, Ma 02139

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Further research on adapting the magnetic balance system for dynamic testing is reported. System improvements are discussed and initial data on a magnetically-suspended ogive cylinder plunging at 2 Hz are reported. Results of a simplified theoretical model for the Magnus force on a spinning body of revolution are also reported.

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INTRODUCTION

For the past two years members of the staff of the M.I.T. Aerophysics Laboratory have been continuing a research program (1) with the magnetic balance system (2) aimed at studying the Magnus effect on bodies of revolution undergoing simultaneous spinning and coning motion. This research program was stimulated by the possibility that introduction of an additional degree of freedom might lead to a better understanding of recent measurements of the Magnus force on ogive cylinders (3) and phenomena observed in surveys of the wakes behind these cylinders (4).

During the earlier research (1) methods for producing the required motion were developed and methods of data reduction were studied. Initial results reported (1,5) lacked the accuracy typical of static tests (3), which was needed for an aerodynamic study.

This report describes research in two areas:

(1) System operational improvements aimed at improving position stability, eliminating noise and improving force calibration linearity. Because the effort to implement these improvements was greater than anticipated, time was not available for more than a few tests using the improved system and techniques. Results from these tests revealed the need for digital data acquisition equipment.

(2) Development of a simplified analytical model for the lifting, spinning body of revolution. This is reported in detail in Reference 6 and is described briefly in this report.

SYSTEM IMPROVEMENTS

As reported in Reference 1, data obtained on a spinning and coning model suffered from excessive scatter and lack of reproducibility as taken with a recording oscillograph. This was traced to several causes:

a) Noise and drift in the position sensing system.
b) Incorrect compensation for a spinning model which narrowed the range of balance operation.
c) Noise from the 1200 Hz roll drive picked up by the data recording system.

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These were all studied and improved. Successful efforts were also made to improve calibration linearity over a wide position range and to improve resolution of the data acquisition system for time varying data signals.

Position Drift

Small unwanted model position changes have been ob-served with the magnetic balance system since its original operation. As these were of the order of .003 to .005 inch in five minutes they were removed by manually adjusting the model position to conform to an optical position zero as observed with two transits (3). This method worked well for static tests. However, it could not be used with a coning model (1). Measurements of model drift as tempera-tures were deliberately varied indicated that this effect was mainly a result of temperature changes in the electronic cabinet and not the EPS coil as had been suspected. A thermostatically controlled cooled air flow was therefore directed into the electronics cabinet and balance area. This reduced long-term drift by a factor of 5 to 7. Consequently, it is now possible to complete a data run without recourse to optical position corrections.

An additional noise source was found to be pick-up of the 1200 Hz roll power by the position sensing system through capacitive coupling to the EPS coil. This problem was circumvented in static tests (3) by shutting off the roll drive during data acquisition. This technique was not possible with a spinning and coning model because of the need for long term data averaging and the need to pre-serve a constant ratio of spinning frequency to coning frequency during a test. This source of noise was reduced to an acceptable level; i.e., the effect of turning the D.C. power and 400 Hz roll field on and off is not detec-table. This was accomplished by installing a grounded electrostatic shield between the EPS coil and the inner saddle coils. This was constructed from a sheet of parallel #36 magnet wires which were cemented together and elec-trically connected to ground. This sheet was constructed by winding the wire around a mandrel, cementing the wires together with polyurethane adhesive, and then splitting the cylinder. Wires were connected together along one side to avoid the formation of closed current loops in the shield.

Permanent Magnet Model

In an effort to develop a model construction technique which would produce a more linear force calibration than the pure iron ellipsoidal cores currently in use, a

permanent magnet core was studied. Samarium-cobalt was found to be the only suitable material with a sufficiently high coersive force that the balance fields would not effect the magnetization level. A standard size ellipsoidal core was therefore constructed from samarium-cobalt discs cemented together with epoxy-resin* and was ground to finish dimension using a silicon carbide wheel. (Because of its high hardness and low strength samarium cobalt was difficult to grind and required a very small cut.) This core was then coated with conducting silver circuit paint and electroplated with .003 - .005 inch of copper.

Precoating with the silver paint was necessary because samarium-cobalt reacts spontaneously with all solutions tested. The model was then magnetized in a 150 kilogauss field at the Francis Bitter National Magnet Laboratory. Operation of this model in the suspension system was normal in all respects.

Since the experimental operation was devoted to evaluating data acquisition methods, time was not available to perform a detailed calibration. Because of its extremely high coersive force it should be possible to treat a samarium-cobalt core as having a fixed, constant magnetization vector. If a small alignment error between the magnetic and geometric axes exists, it can be determined experimentally.

Spinning Model Compensator

In the course of operating with a spinning and coning model it became apparent that performance had to be compromised in order to find control settings that would allow the combined motion. This is a result of the gyroscopic moment of the spinning model and can be seen by inspection of the Euler equations using principal body axes with x along the axis of symmetry, which is the spin axis.

For the roll axis,

$$M_x = I_{xx} \frac{d\omega_x}{dt} - (I_{yy} - I_{zz})\omega_y \omega_z$$

Since $I_{yy} = I_{zz}$ for a body of revolution, the cross term vanishes, so there is no pitch or yaw coupling to roll.

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*Equal parts of Shell Epon 815 resin and V-40 hardener.

For the pitch axis,

$$M_y = I_{yy} \frac{d\omega_y}{dt} - (I_{zz}-I_{xx})\omega_z\omega_x$$

$$M_y = M_{y\ Mag} - C_M Sq = I_{yy} \frac{d\omega_y}{dt} - (I_{zz}-I_{xx})\omega_x\omega_z$$

Similarly for the yaw axis

$$M_z = M_{z\ mag} - C_n Sq = I_{zz} \frac{d\omega_z}{dt} - (I_{yy}-I_{xx})\omega_x\omega_y$$

The effect of spin (ω_x) can be seen in the introduction of the gyroscopic terms. These are the terms proportional to spin rate times yawing velocity in the pitch equation and spin rate times pitching velocity in the yaw equation.

The circuit in Figure 1 has been designed to neutralize these terms by the addition of their negatives to the power supply input. This circuit consists of a roll rate converter to produce a D.C. signal proportional to spin rate (ω_x), differentiation to obtain pitch rate and yaw rate from pitch position and yaw position, multipliers to form the product terms, gain adjustments and lead lag compensation to neutralize the lags due to magnet coil and generator field.

Limited experience with this circuit indicates it greatly improves the stability of a spinning model.

EXPERIMENTAL OPERATION

Because previous measurements (1) using the Sanborn oscillograph to record time varying data lacked sufficient resolution and the inertial signal nulling had proved inaccurate, data was taken by the second method originally proposed (1,5). This method used the Spectral Dynamics tracking filters to extract the amplitude and phase of the

fundamental frequency component of the data signals. The data system used is shown in Figure 2. Here the integrating digital voltmeter is used to accurately average and print each data variable. To insure that the period of integration is always an integral number of cycles a digital counter is used to carefully adjust the operating frequency to an integral number of cycles per second and the voltmeter is used to integrate for one second. This method was also used in addition to the oscilloscope to monitor the amplitude of model motion.

This made possible much more precise control of model motion amplitude than was possible previously using the oscilloscope. Using the position signal of 200 millivolts for .250 inch displacement the resolution of .2 mv on the digital counter represents .1% compared to 2% for the oscilloscope.

Using this method of data processing, runs were made with the ogive cylinder model undergoing non-spinning, plunging motion of about .18 inch (.18 model diameter) total displacement at 2 Hz and speeds of 19.4, 101 and 302 fps.* Lift, drag and pitching moment were measured, and repeatable self-consistent data were obtained as listed in Table 1. Since 2 Hz was near the plunge resonant frequency, aerodynamic moments were in phase with the inertial forces and moments.

Pitching moment was determined from a calibration of magnetic stiffness against measured pitch position from the EPS system. This provided much greater pitch sensitivity than was possible from currents.

A review of the data to determine why this was the case and why the pitching motion could not be completely removed by nulling indicated that the method of connecting the pitch and yaw coils which had been developed for static tests and used for all previous work made it impossible to separate completely pitch and yaw signals at frequencies above .5 Hz. This necessitated the deflection technique for determining pitching moment and was the cause of imperfect nulling of model pitching motion.

The difficulty arises because the inner and outer saddle coils have different time constants resulting from their different physical size. Further, these coils are wound at 45 degrees to the pitch and yaw axes and the pitch and yaw signals are mixed before being directed to the appropriate coil. Because of the different time constants any mix of signals which is correct under steady conditions becomes increasingly incorrect as frequency is increased.

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*The 19.4 case was the speed at which the signal was indistinguishable from the noise. Hence, this data was used as a measure of error.

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Table 1

Data on Plunging Model
at 2.0 Hz

	101 fps	302 fps
$\theta_{radians}$	.0054	.0083
$\frac{w}{u} = \alpha$	.0019	.0006
Z amplitude, inch	.1827	.1807
Lift (Pounds)		
$L_{measured}$	.0574	.0584
$L_{inertial}$	.0568	.0562
$\Delta L \pm .0002$	+.00065	+.0021
C_L in phase with L_i	+.0099	+.003
Moment (Inch Pounds)		
M_{total}	.0193	.0294
M_I	.00897	.00889
ΔM	.0103	.0205
C_m* in phase with M_I	.016	.004

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*C_m about half length.

The method of correcting this difficulty appears
straightforward. Instead of mixing pitch and yaw signals
after the compensation and before the coils, the signals
should be mixed immediately after the EPS. Model motion
should then be resolved and forces measured about the
natural coil axes which are 45 degrees to the present
coordinates. A rotation of axes could then be performed
to return to the laboratory coordinates. This requires
reconnection of the signal leads in the control loop and
a somewhat more complicated method of data reduction to
account for the 45 degree shift in magnetic axes.

ANALYTICAL MODEL

In the course of the experimental work it became clear
that an analytical model would be needed to interpret the
anticipated data in the light of previous results. Effort
was therefore devoted to setting up and using such a
simplified model for computation of Magnus force. A model
was sought which would provide a means of calculating Magnus
force in both normal and reverse regions. As this work is
reported in detail in Reference 6, it will only be
summarized here.

The model developed approximates the vorticity shed
by the nose as two discrete vortices which interact with
the body as they are convected downstream. Details of the
procedure for choosing the spring points and calculating
vortex growth from Reference 6 will not be repeated here,
but some results are worth noting. Figure 3 shows the re-
sults of the calculations compared to 9.5 degree data from
Reference 3. Agreement is reasonable at this angle of
attack. At small angles of attack while the correct negative
sign is predicted the magnitude is too small by a factor of
10, as can be seen in Figure 4. It should be noted that at
these low angles of attack the vortex pair move more or less
parallel to the body. The initial condition ($r/a=1.005$) is
sufficient to clear the boundary layer. However, at the
base of the body the boundary layer is sufficiently thick
that the implicit assumption of a non-interacting vortex
and boundary layer is probably invalid. If one includes
the axial displacement thickness in the calculation the in-
cremental vortex motion more than doubles, which increases
the strength of the vortex in turn. Hence the factor of 10
is reduced to between 2.5 and 3 by this procedure.

However, the vortex and boundary layer would seem to be
so closely coupled that an ad hoc procedure allowing for the
boundary layer effect on the vortex trajectory without allow-
ing for the effect of the vortex on the boundary layer is

difficult to justify, and hence was not used. Nevertheless, the need for a more sophisticated model, including vortex boundary layer interaction, is clear.

CONCLUSIONS and RECOMMENDATIONS

Significant improvements were made in the accuracy and stability of the position sensing system and compensation system for a spinning model. Use of tracking filters and the integrating digital voltmeter provided a means of accurately measuring the time varying quantities needed for data acquisition from an oscillating model. The increased sensitivity of the improved system revealed the need for changing the method of connecting pitch and yaw coil drive signals for operation with oscillating models.

The improved system requires data acquisition equipment for efficient operation to provide the necessary high resolution for subtracting out large inertial loads, provide rapid data acquisition for increased productivity, and provide the data in a form that will allow compatibility with modern data processing techniques.

These data indicate the level of resolution possible from the system. In the case of the plunging motion with very small induced angles of attack, subtraction of the inertial loads indicates even greater accuracy is desirable. For pitching motion the aerodynamic forces would be about ten times larger compared to the inertial forces and the resulting accuracy better by this factor.

Accurately controlled model periodic motion shows the capability for producing combined motion which can separate the derivatives C_{M_q} and $C_{M_{\dot{\alpha}}}$ and provide a means of measuring them independently. A digital data system will be required for good productivity of such experiments.

The vortex analytical model developed (6) has shown the capability for producing both positive and negative Magnus forces and the positive force agrees well with experiments at low spin and moderate angles of attack. The negative force calculated is too small. This model should be extended by increasing the number of discrete vortices and providing for mutual interaction between these vortices and the body boundary layer. This should improve accuracy in the negative force and high angle regions.

PUBLICATIONS

"New Techniques for Production of Combined Spinning and Coning Motion with Magnetically-Suspended Wind Tunnel Models", 8th International Congress on Instrumentation in Aerospace Simulation Facilities, U.S. Naval Postgraduate School, Monterey, California, Sept., 1979.

"A Vortex Model for Magnus Forces at Low Speeds, Spins and Angles" by E E Covert and D S Eberhardt, submitted to the AIAA, Jan., 1981.

PERSONNEL

Scientific personnel who contributed to this research program are:

Professor Eugene E. Covert

Professor Morton Finston

Dr Charles W Haldeman

Mr D Scott Eberhardt

Mr Charles E Hawks

Mr James L Nash

Mr. Eberhardt expects to be awarded the M.S. degree during the Spring semester of 1981.

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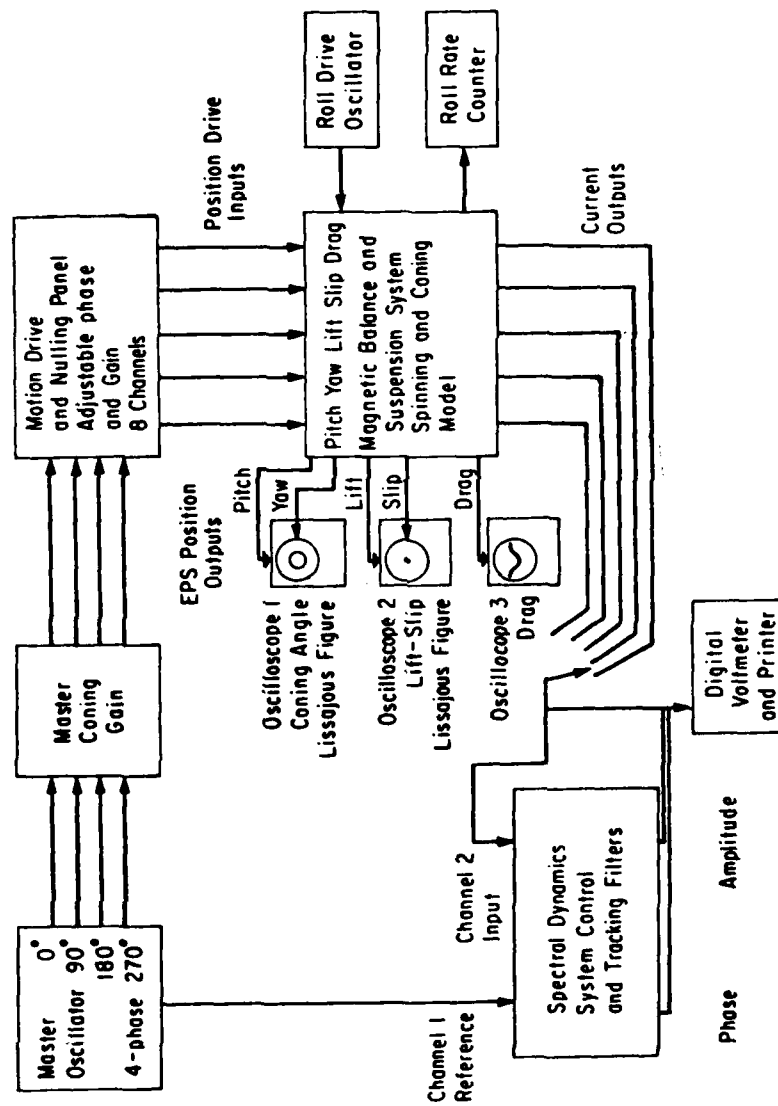
Figure 1. Spinning Compensation Circuit

Figure 2. System used to replace Sanborn Recorder for making dynamic measurements

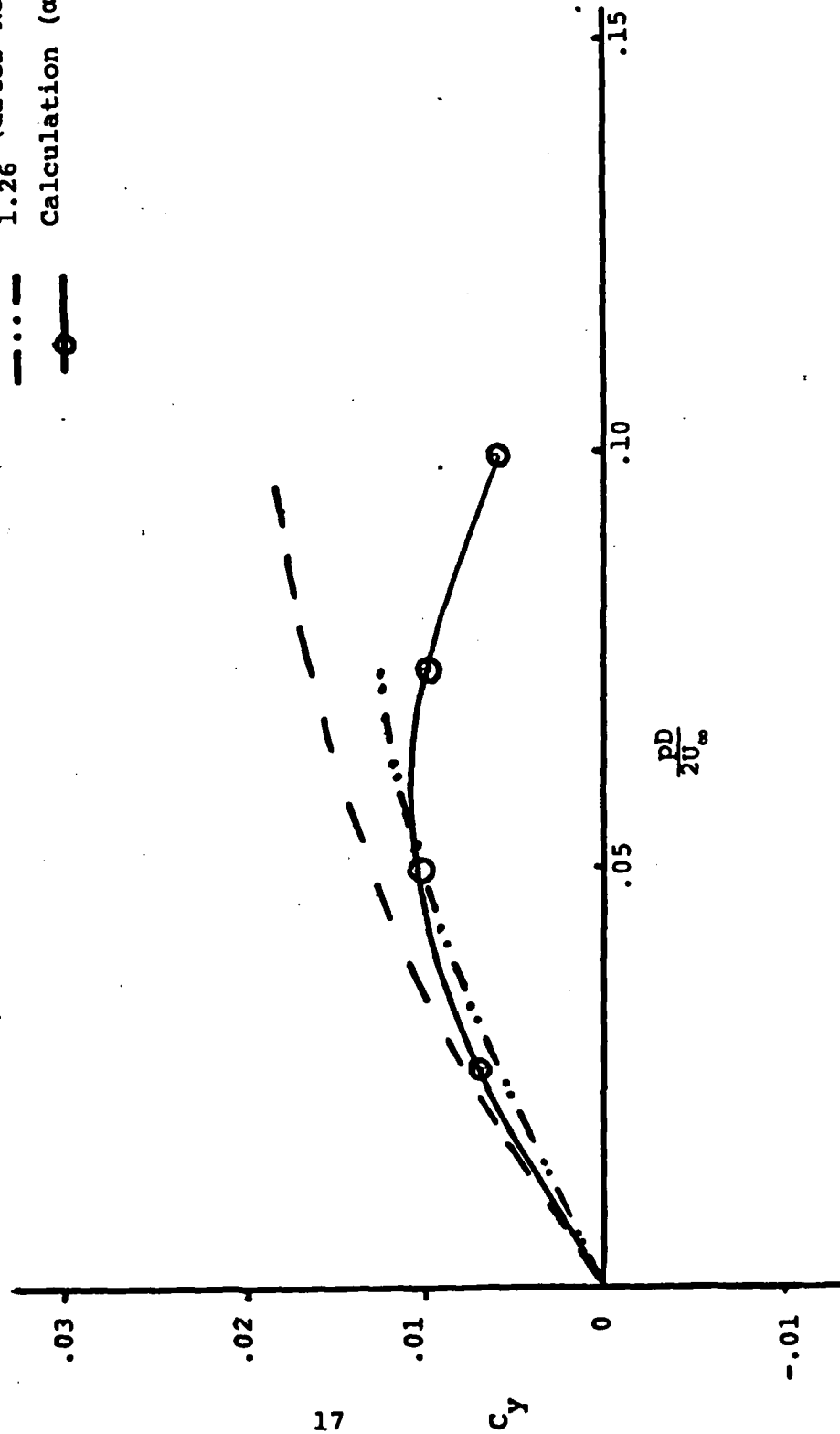Figure 3. Reynolds Number Effect C_y vs. $PD/2U_\infty$; $\alpha=9.5$

Figure 4. Side-Force Coefficient vs α at $\frac{pD}{2U_\infty}$ = 0.0450 (fineness Ratio 5)